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# Improved Drilling Performance in Lake Maracaibo Using a Low-Salinity High-Performance Water-Based Drilling Fluid

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## Abstract

The complexity of Icotea and Misoa wells drilled in the West Urdaneta Field of Lake Maracaibo has continually increased in recent years. Development operations continue and economics have improved with advancements in drilling technology, such as rotary steerable assemblies, logging-while-drilling (LWD) tools, annular pressure subs and new bit designs. However, significant drilling problems associated with borehole instability and lost circulation have continued to burden well delivery costs.

Throughout the drilling history of this field, a variety of non-aqueous fluids (NAF) and water-based muds (WBM) have been used in an attempt to resolve these drilling problems. Wellbore instability, as manifested by an almost continual caving of shales in the La Rosa formation, and lost circulation proved problematic with NAF when drilling the Icotea and Misoa formations. A variety of different WBM were used subsequently. These applications, in turn, were plagued by problems with hole enlargement, bit balling, accretion, low rates-of-penetration, insufficient hole cleaning and associated need for excessive backreaming.

An extensive study was undertaken to identify an appropriate drilling fluid design that would facilitate optimum drilling performance and achieve important environmental objectives. The latter dictated the use of an environmentally benign, low-salinity system. A new high-performance water-based mud (HPWBM) was field tested in the intermediate section of the Icotea and Misoa wells. For the two well types, the HPWBM was used to drill the problematic Laguna, Lagunillas, and La Rosa formations. Subsequently, the HPWBM was used to transverse the upper Icotea formations or the upper Misoa formations depending on the production interval target.

Through a process of field tests, after action reviews (AAR), and communications between PERLA and its service providers, the performance of these wells continually improved and ultimately set new performance benchmarks. The superiority of the new HPWBM system has now made it the system of choice for drilling intermediate hole sections in the West Urdaneta Field.

This paper provides a detailed technical overview of the new HPWBM and presents case histories comparing performance to offset wells previously drilled with NAF and conventional WBM systems.

## Introduction

The exploration and production (E&P) industry is increasingly drilling more technically challenging and difficult wells. Exploration and development operations have expanded globally as the economics of exploring for producing oil and gas have improved. Moreover, advances in drilling technology have enabled the routine drilling of extended reach and horizontal wells even though such wells present considerable technical and economical challenges and risks.

Throughout the drilling history of the West Urdaneta intermediate sections, the variety of inhibitive WBMs used in the hope of alleviating drilling problems inherent to the field achieved only limited success. Improvements in rates-of-penetration (ROP) were noted when using dispersed WBM. However, these systems were accompanied by excessive hole enlargement, clay instability, problematic trips, pack-off and lost circulation events. Attempts to use more highly inhibitive systems were made thereafter... While these systems yielded satisfactory clay- and shale stability, their benefits were often offset by problems arising from accretion and associated ROP reduction.

Subsequently, an attempt was made to improve fluid performance through use of non-aqueous fluid (NAF). While effective in reducing accretion and resulting increases in ROP, the wells drilled with NAF were problematic due to continual generation of cavings (creating problems with hole cleaning, tripping pipe, etc.) and catastrophic lost circulation events.

After analysis of the offset wells and conducting a complete study that involved shale characterization and fluid design, a HPWBM system was selected to be used for drilling through the problematic Laguna, Lagunilla and La Rosa formations. This system was designed to provide improvements in ROP (by reducing bit balling and accretion.) and wellbore stability compared to conventional WBM. Reduced friction in this HPWBM system reduces torque and drag, thereby facilitating transfer of weight to the bit required for the aggressive directional plan for the wells.

## Non-Aqueous Fluids

High-performance fluids (HPF) are defined as drilling fluids used to drill technically challenging and inherently costly wells. Cost reduction achieved through superior technical performance is the key driver in selecting the appropriate HPF for a given well. NAF are the "benchmark" high-performance fluid because of superior technical performance in areas of: 1) shale stability, 2) clay and cuttings inhibition, 3) increased rates-of-penetration, 4) reduced bit balling and accretion, and 5) torque and drag reduction.

Shales compose roughly 75% of the formations drilled and shale instability is the root cause of over 90% of the well-bore instability-related problems. The most important variable in maintaining shale stability is preventing pressure invasion into the shale matrix.[1,2,3] Shale stability is achieved when pressure invasion is eliminated or strongly reduced and differential pressure support is maintained at the wall of the wellbore. The mechanisms available to shut-off pressure invasion center around restricting Darcy flow into the shale matrix by: 1) plugging pore throats, 2) slowing down invasion by making the invading filtrate more viscous, 3) balancing hydraulic Darcy flow with osmotic backflow, or 4) a combination of the previous mechanisms. For instance, plugging pore throats (mechanism 1) will enhance the natural, "leaky" membrane efficiency of shale to make it more selective and more effective in reducing the movement of solutes into the shale. Coupled with an osmotic pressure differential (derived from a difference in chemical potential / activity / salinity between the mud and the shale), this may enhance the osmotic backflow effect (mechanism 3).

The hydration and dispersion of reactive clays can lead to problems such as bit balling, accretion, poor solids removal efficiency, high dilution rates, and problems managing rheological and filtration control properties. Clay hydration and chemical dispersion is prevented when using NAF due to isolation of the clay surface by preferential oil-wetting, coupled with beneficial osmotic effects generated by the low water-phase activity of the brine phase.

NAF are the preferred fluid for many drilling operations because they enable high rates-of-penetration when used in combination with PDC bits. Oil-wetting agents in NAF preferentially oil-wet the drilling assembly and bit and prevent the adherence of clay-rich cuttings onto metal surfaces. Among the many benefits are extended bit life with an associated reduction in the number of bit trips, and the absence of bit balling which increases ROP.

The advantages of NAF also have associated costs and risks including a relatively high unit technical cost, environmental risks, more complicated waste management and higher waste disposal cost, and increased risk of lost circulation.[4] Wetting and fracture propagation characteristics of NAF yield a low threshold towards inducing formation fracturing and lost circulation. Consequently, NAF may yield catastrophic losses of whole mud with extreme difficulty to heal the formation using lost circulation materials. Additionally, maintaining wellbore stability in micro-fractured formations (as frequently encountered in the tectonically stressed formations throughout South America) may be very cumbersome using NAF. Penetration of NAF into micro-fractures in shale can lubricate these fractures and equilibrate the pore pressure in these fractures with the mud pressure whereby effective mud pressure support from overbalance is lost. Annular pressure fluctuations, particularly those associated with making connections, will then lead to continual cavings into the wellbore. This has happened time and again when Icotea and Misoa wells were drilled with NAF, ultimately leading to their disqualification.

## New High-Performance Water-Based Mud

Shale stability in the new HPWBM is obtained by reducing pore pressure transmission, as outlined. A more selective membrane is generated in the new HPWBM using both mechanical and chemical means to augment the natural leaky membrane. First, a micronized, deformable sealing polymer is used to mechanically bridge shale pore throats and micro-fractures. The polymer maintains a stable particle size distribution even in the presence of high salt concentrations. The particle size and deformable nature of the polymer is such that it will bridge and mold itself along fractures, further improving bridging (plugging) efficiency.

Secondly, an internal bridge, obtained via precipitation within the shale pore throats and fractures, is generated using aluminate chemistry.[5] The aluminate complex is soluble in the mud but precipitates as it enters the shale matrix due to a reduction in pH, reaction with multivalent cations, or a combination of both. An independent study of pore pressure transmission and membrane efficiency in shale concluded that aluminates (and silicates) provide the highest membrane efficiencies of WBM.[6] Figure 1 compares the performance of the HPWBM against conventional WBM and NAF in terms of membrane efficiency and effects on pore pressure transmission. The results show that the HPWBM system shows the same characteristics of preventing mud pressure penetration and causing osmotic shale hydration as a high-salinity invert NAF.

The HPWBM furthermore uses a clay hydration suppressant (CHS) to stabilize highly reactive clays through a mechanism of cation exchange. The CHS inhibits reactive clays from hydrating and becoming plastic, which provides a secondary benefit of reducing the tendency towards bit balling.

Anti-balling and accretion additives are used in water-based muds to preferentially oil-wet the bit and drill string in a manner similar to NAF. The most effective ROP enhancers are those formulated to create an "oil-like" film on metal and rock surfaces.[7,8] The term "oil" is used figuratively to describe the physical characteristics of the film rather than the actual chemical composition. The HPWBM contains an ROP enhancer and anti-accretion additive designed to preferentially oil-wet metal and shale surfaces using environmentally-approved base fluids and surfactants. The additive coats the metal surfaces, thereby reducing the tendency of hydrated clays and cuttings to adhere to metal surfaces. The material also minimizes the agglomeration of cuttings to one another, which leads to improved hole cleaning efficiency.

A proprietary method of addition is used to inject the anti-balling additive, so that a continual, non-emulsified stream of the material is available at the bit while drilling. This unique method-of-use provides a step change in performance by minimizing mechanical emulsification and reducing concentrations needed to deliver performance.

Finally, partially hydrolyzed polyacrylamide (PHPA) polymer is used to minimize disintegration of the cuttings as they are circulated from the annulus. PHPA are large, anionic molecules that attach to positive sites on cuttings and encapsulate them to minimize disintegration and improve the efficiency of their removal by the rig's solids control equipment.

### *Environmental Considerations*

Environmental legislation governing drilling waste is continually restricting the discharge limits of spent muds and drilled cuttings. Operators are challenged with achieving a balance between minimizing the potential environmental impact of the drilling fluid against drilling objectives.

Operators have used a variety of methods for managing drilling wastes, typically driven by governmental regulations and cost considerations. Three options exist to manage wastes from drilled cuttings and spent drilling fluid: discharge, down hole injection, and onshore disposal, which includes land farming.[9] All options have advantages and disadvantages with regard to total life cycle environmental impact, safety, cost, and operational performance.

In addition to the aforementioned drilling problems that have plagued this field, Venezuela has strict environmental regulations governing the disposal of drilling wastes into offshore waters; in particular in Lake Maracaibo, where the requirements for managing environmental waste are becoming more stringent. As a result, the discharge of drilling fluids and associated drilling waste is absolutely prohibited in Lake Maracaibo. Alternative disposal options are available with land farming being the most commonly used method. The permitting process is less restrictive with land farming compared to other disposal methods; however, land farming is increasingly becoming impractical due to space limitations.

Costs associated with waste management are not trivial and the total cost of waste management is more than the logistical cost of collecting and disposing of the waste. It has been reported that WBM can generate between 7,000 to 13,000 bbls of waste per well, of which 1,400 to 2,800 are drilled cuttings.[10] The major component of the drilling wastes affecting the ability to land farm is the chloride content, with an upper limit of 2,500 mg/L of chlorides considered acceptable for land farming in Venezuela. The water salinity in Lake Maracaibo (3,500 – 4,000 mg/L) exceeds this upper requirement.

The HPWBM system used on original well drilled with the HPWBM (Well #1) was formulated with ~ 19% NaCl (130,000 mg/L chlorides). The high chloride content of this fluid requires a higher than normal land consumption in order to distribute the waste at equivalent levels of lower salinity muds. Through careful review and well information, including an after action review (AAR) process, the decision was made to move towards drilling future wells with a lower salinity HPWBM to achieve drilling performance and environmental objectives. The new HPWBM provided substantial additional operational improvement and environmental compliance such that it is considered the preferred system in the continued development of the West Urdaneta field.

## Comparison of Drilling Fluids Systems

A systematic study was conducted to evaluate HPWBM fluids as a possible alternative to replace the WBM in use in the 12 ¼" hole section of the West Urdaneta Field. The HPWBM fluid was evaluated alongside three WBM's previously used in the area, as well as NAF. The test matrix involved the evaluation of the following fluid formulations:

- WBM #1
- WBM #2
- WBM #3
- HPWBM (20 % NaCl)
- HPWBM (0.4% NaCl)
- 80/20 NAF

Drill cuttings samples from the 12 ¼" hole section of a previously drilled well (ICE-05) were characterized at depths of 4,700, 9,500, and 11,100 feet (Laguna, La Rosa, and Icotea formations, respectively) using X-ray diffraction analysis. X-ray diffraction data indicated that Laguna, La Rosa, and Icotea formations contained high kaolinite content with a low amount of mixed-layer clay (Table 1). The formation cuttings were cleaned, dried and then used to prepare reconstituted shale wafers. The evaluations were made with the shale samples from the Icotea formation.

Inhibition of swelling, hydration and dispersion of formation material was evaluated using the static shale wafer test procedure. This procedure measures the ability of additives or fluids to stabilize reactive and dispersive clays by reducing shale swelling and hydration over a measured time period. A Performance Index (PI), calculated as the sum of the percentage change in hardness, swelling and hydration, was the metric used to characterize the relative performance of each fluid.

Shale wafer tests are indirect indicators of the expected performance of these fluids, and other key stability mechanisms, such as pore pressure transmission, cannot be quantified using these tests. Wafer tests are of limited value in quantifying shale inhibition characteristics; however, they are simple and well suited for making qualitative, side-by-side comparisons of fluid systems for clay and cuttings stability.

The fluid formulations were mixed and hot rolled for 16 hours at 180° F. Afterwards, rheological and filtration control tests were conducted to ensure that measured properties were at expected levels. Detailed information on the fluid formulations and properties appear in Tables 2 and 3. The HPWBM formulations were optimized to obtain rheological properties similar to the WBM systems previously used in the field. Of specific interest was the HPWBM formulations and how they compared to WBM #1 and NAF.

Results obtained from the wafer dispersion and stability tests are presented in Table 4. The 20% NaCl HPWBM showed little tendency towards hydration, swelling and hardness change of the wafer, generating a favorable Performance Index (PI) compared to the other WBM. The PI of the HPWBM fluid formulated with 20% with NaCl was very similar to that of NAF.

Accretion tests were also performed on these same formulations. The accretion tests were conducted using a procedure developed by Shell, which utilizes formation materials and a metal bar representative of the metallurgy of the drilling assembly. The bar is placed into a container with the drilling fluid and formation material, usually cuttings. Accretion is defined as the percentage weight change of the metal bar, before and after heat aging and exposure to the fluid and formation materials. Ideally, there should be no change in the weight of the bar after aging, indicating that formation materials did not adhere (accrete) to the metal during the tests. The results presented in Table 5 show that the lowest tendency towards accretion, as measured by weight change of the bar, occurred with NAF, followed by the 20% NaCl HPWBM formulation.

## Case Histories

The encouraging results from the laboratory testing of the HPWBM suggested that it would be a high-performing alternative to the conventional WBM used on Icotea wells. The team involved in the evaluation and qualification process carried out an extensive peer review and pre-well planning process prior to the start of field tests. Key performance metrics, roles and responsibilities, training and lines of communication were identified and clearly established.

### *Well #1*

The first well was drilled with the 20% NaCl HPWBM due to favorable comparison to NAF in the evaluation process. Well #1 was the most challenging well to be drilled in the 2005 drilling campaign with respect to directional complexity. Key performance indicators for the 12 ¼" hole section of Well #1 were established prior to the start of the well, using four reference offset wells for comparison.

It was decided that the initial test well would be drilled with the high-salinity system, which had performed well in the lab evaluations. After well execution, its performance would be evaluated and then the formulation would be changed and optimized to fully align with both drilling performance and environmental objectives. The high salinity (chloride content) was recognized as being problematic with respect to waste management; however, the expected benefits derived in meeting drilling objectives outweighed the waste management and disposal costs associated with the high-salt system.

A low solids, non-dispersed (LSND) system was used to drill the first part of the 12 ¼" hole section. Use of the rate-of-penetration (ROP) enhancer began with the LSND system and was followed by a 50% increase in ROP. Afterwards, the well was displaced to the HPWBM at 6,405', with a 2,000 ft-lb reduction in downhole torque. The well was drilled to a depth of 7,302 feet without problems and the drill string was pulled from the hole. The bit and near-bit stabilizer were free from bit balling and accretion. Figures 2 and 3 compare the bit and BHA for the HPWBM compared to the previous offset well drilled with conventional WBM. Rates of penetration were continually monitored for comparison against an expectation of achieving an average ROP in excess of 50 feet per hour. A plot of ROP versus measured depth is presented in Figure 4. ROP on Well #1 averaged 75 feet per hour. Another key performance expectation in selecting the system was to manage or eliminate cavings arising from the La Rosa shale. This formation was drilled with noted improvements in terms of the size, volume and frequency of La Rosa formation material.

The well was drilled to a depth of 8,121 feet with a directional assembly and the rig lost power for 2 ½ hours, leaving the drill string stationary in the hole. After regaining power, the drill string was picked up and tripping operations continued without problems.

Operations resumed to a depth of 9,108' where the backreaming operations began and the pipe became stuck due to a combination of variables that included insufficient mud weight to guarantee mechanical wellbore stability and reduced flow rates associated with failure of the rig's mud pumps and solids control equipment. Fishing operations were unsuccessful, so a cement kick off plug was set for the well to be side-tracked.

### *Well #1 ST*

Approximately 50 % of the mud volume from Well #1 was used to drill the Well #1 ST (side-track) well. The kick off plug was drilled with a rotary steerable assembly washing through, and then drilling, 600 feet of soft and firm cement. The well was directionally drilled without problems to a depth of 8,706 feet at an average ROP of 90 feet per hour.

Torque input information including pick-up, slack-off, hookload and off-bottom rotating torque was collected on every connection, roughly 93 foot stand length. The off-bottom rotating torque (ROB) was used as a surface torque input to calculate friction factors. This modeling was done at the well-site using measured survey and drill string data from the MWD service provider. Figure 5 compares the ROB and friction factors as a function of measured depth. The data show that the friction factor decreases with increased depth, occurring because of increased concentrations of the ROP enhancer and small additions of NAF for enhanced lubrication. The average friction factor for the interval was 0.28 vs. 0.40 predicted by the MWD provider in pre-well planning.

Downhole indicators from tripping conditions suggested that the wellbore was stable. Trips were generally trouble-free and performed without use of the top drive or mud pumps. The well was drilled to a total depth of 9,770 feet where the wellbore was circulated at high flow rates to ensure hole cleaning and the assembly was tripped out of the hole on elevators, without the need for the rotary or mud pumps. The 9 ⅝-inch casing was picked up and run into the hole to a depth of 8,970 feet where it became differentially stuck in the area of the hole with the highest dog-leg severity (6.8°/100 feet).

### *After Action Review (AAR) Process*

An after action review process was used to evaluate all operational aspects of the Well #1 and Well #1 ST. The purpose of the AAR was to evaluate the peer review, planning and field testing phases of this project. A committed effort was made between the parties involved to fully and objectively use the AAR process to drive improvements for the Urdaneta drilling campaign. Key elements of the AAR process included: 1) what was planned, 2) what was achieved, 3) highlights, 4) areas of improvements, 5) lessons learned and 6) recommendations. Findings of the AAR process included:

**Highlights**

- 50% increase in ROP through use of ROP enhancer
- Immediate reduction in downhole torque (2 K ft-lbs) after displacing to HPWBM
- First well in the Urdaneta field which did not require back reaming on all trips
- No incidents of bit balling and accretion
- ROP met or exceeded expectations
- Stability of LaRosa formation
- Dilution rates were lower than planned
- Product consumption was lower than programmed

**Areas of Improvement**

- Problems transferring weight to the bit when sliding
- Environmentally acceptable secondary lubricants are necessary
- Hole cleaning problematic due to problems with mud pumps and solids control equipment
- Disposal problems with high-salinity HPWBM
- Improved fluid loss control to prevent differential sticking on casing runs

**Lessons Learned**

- The rig capabilities were pushed to the limit
- Pre-well planning was sufficient to address fluid related aspects of the operation
- Pre-well planning was insufficient to address rig capabilities, drilling practices and technology transfer
- Measurable improvements in fluids-related performance observed with HPWBM
- Formations drilled have low salinity (3,000 mg/L)

**Recommendations**

- Low-salinity HPWBM for future wells to match formation salinity
- Investigate reuse and recycling of HPWBM
- Monitor hole cleaning with hydraulics models coupled with MWD turbine data
- Audit and perform remedial work on solids control equipment
- Use of environmentally benign lubricants for added torque and drag reduction

### *Well #2*

Well #2 was drilled after having completed the AAR process and a pause in the drilling program. The AAR process indicated that a low-salinity HPWBM was potentially more suitable for West Urdaneta wells due to formation salinities in the field. Lessons learned and recommendations from the AAR process were carefully reviewed, agreed upon and implemented prior to the start of Well #2.

Lake Maracaibo water was chosen as the base fluid for this application because of logistical and rig space limitations associated with using 20% NaCl. The lower salinity of the lake water (4,000 mg/L) also reduced disposal costs for spent drilling fluid and cuttings. The HPWBM system met all performance expectations while drilling over 6,000 ft of 12 ¼" hole with a rotary steerable tool. The directional profile of this interval was challenging, building in inclination from near-vertical to 88º. The azimuth of the hole was also changed by approximately 160º.

Highly resilient, spherical graphite, along with a blend of organic surfactants and modified fatty acid compounds, were added to supplement the lubricity provided by the HPWBM. This helped reduce torque associated with the aggressive directional plan. The differential sticking prevention ability of the HPWBM system was put to the test near the end of the interval. Due to rig equipment failures, the pipe was static in the open hole for over two hours while repairs were being made. After the repairs were made, the pipe was pulled free with no problems.

The final test against differential sticking came when running the 9 ⅝-inch casing. Wells in this area have a history of getting stuck while running casing. Over 10,600 ft. of casing was run to bottom and cemented without problems.

### *Well #3*

Well #3 was the second application of low-salinity HPWBM in drilling the 12 ¼" intermediate interval. The system met all performance expectations while drilling over 3,450 ft of 12 ¼" hole with a rotary steerable tool. The directional profile of this interval was challenging, building in inclination from near-vertical to 81º. The azimuth change on the well was as high as 16º.

Torque and drag were managed through use of the spherical, resilient graphite and supplemental lubricant. The learning curve with the HPWBM was improved on this well as indicated by the reduction in days per thousand feet, which was reduced by 17% in Well #3 as compared with Well #2.

### Well #4

Well #4 was the third application of low-salinity HPWBM and approximately 900 barrels of HPWBM left from Well #3 well were recycled for use on this well. New volume was prepared at the liquid mud plant using doubled product concentrations. This newly built mud volume was then diluted back after delivery to the well-site as part of a strategy to improve logistics and minimize the dependency on the liquid mud plant and dedicated work boats.

Although the system performed well in Well #2 and Well #3, the challenges faced in Well #4 (due to non-fluids related extended wellbore exposure time) pushed the HPWBM system to its technical limits and proved its capability to maintain stability even in worst case scenarios. The system met all performance expectations while drilling over 4,580 ft of 12 ¼" hole with a rotary steerable assembly.

The directional profile of this interval was challenging, building in inclination from near-vertical to 88º. The well trajectory needed to be corrected due to suspected variation on target depth and the hole angle was dropped to 84º. The 9 ⅝-inch casing hung at 10,380 ft. due to hole geometry problems and lost circulation was experienced.

This variation of the original plan represented a major challenge for the HPWBM system. Despite the mechanical difficulties, the HPWBM made it possible to 1) pull out the 9 ⅝-inch casing with no problems, 2) condition the hole geometry with no wellbore problems, 3) leave the hole open with no circulation for 72 hours, 4) run casing to within 10 feet of total depth, and 5) pump out a lost circulation material (LCM) squeeze to protect exposed low pressure sands.

### Field Test Comparison

A comparison of key well data, which includes dilution rates, average ROP and average friction factors, is presented in Figures 6-8. Key performance metrics were established in the pre-well planning process and compare favorably to field performance of the system. The performance metric for dilution rate was 0.7 bbls per foot, and three out of the four wells were below this limit. The average dilution rate of the four wells presented in Figure 6 was 0.6 bbls per foot.

Rates of penetration were another key performance metric, to facilitate the use of PDC bits and reduce rig time. The key metric for ROP was to achieve at an average rate in excess of 50 feet per hour. Again, the ROP on three out of the four wells exceeded this expectation, averaging 59 feet per hour (Figure 7). The one well that did not meet this metric (ICE-09) used a rock bit instead of a PDC bit, for directional control objectives. It is believed that the ROP metric was not achieved on this well because of the bit type used.

Lastly, torque and drag reduction was a key performance metric for these wells due to the aggressive trajectory and geometry. Pre-well planning was based on the assumption that the fluid would exhibit a friction factor of 0.4. Friction factors were calculated at the well site, using field torque measurements and are presented in Figure 8. The average friction factor for these wells was 0.24, which compares favorably to expectations and allowed for meeting directional objectives without torque and drag related problems.

The performance of the HPWBM in field tests was consistent with results from the laboratory evaluation and qualification process. Quite often this is not the case with other HPWBM, which appear promising from a laboratory perspective, but operationally do not perform well in the field. The authors view this system as unique, compared to other HPWBM, in that the operational performance in the field exceeded expectations based on laboratory evaluations.

## Conclusions

- A new HPWBM has been developed and successfully field tested in the West Urdaneta field of Lake Maracaibo.
- The HPWBM was introduced via a collaborative team effort between PERFLA, Shell and BHDF.
- An after action review process was used during field testing to capture and share learnings that could be used to progressively improve environmental and drilling performance.
- Improved operational performance was observed with the low-salinity HPWBM system, compared to that of the high-salinity system.
- The low-salinity HPWBM fully satisfies all environmental and operational objectives.
- The HPWBM is unique in that field performance exceeded expectations based on laboratory analysis.
- The system has set new performance benchmarks and become the preferred fluid-of-choice for the West Urdaneta field.

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## Nomenclature

*Mg/L = concentration, milligrams per litre*
*Lbs/gal= mud density, pounds per gallon*
*MBT = Methylene Blue Test*
*NaCl = salt, sodium chloride*
*bbl = oilfield barrel, 42 gallons*
*PDC = polycrystalline diamond cutters*
*PSI = pressure, pounds/inch$^2$*
*bbls/ft = dilution rate, barrels per foot*
*F = temperature, degrees Fahrenheit*
*Ft-lbs = torque, foot-pounds*
*$Ft^2$ = area, square feet*
*$CaCO_3$ = calcium carbonate*
*BHA = bottom-hole assembly*
*PV = Plastic Viscosity*
*cP = viscosity, centipoise*
*YP = Yield Point*
*lbs/bbl = concentration, pounds per barrel*
*MWD = Measurement-While-Drilling*
*HPHT = High-pressure, High-temperature*
*API = American Petroleum Institute*
*lbs/100 $ft^2$ = pounds per 100 square feet*
*ml = volume, milliliters*
*CMC = carboxy-methyl cellulose*
*NaOH = sodium hydroxide*
*$CaCl_2$ = calcium chloride*
*Vol = volume*

**Table 1. X-ray diffraction of shale sample from Icotea well**

| Composition | Formation | | |
|---|---|---|---|
| | Laguna | La Rosa | Icotea |
| Quartz, % | 20-25 | 15-20 | 5-10 |
| Illite, % | <5 | 10-15 | 25-30 |
| Kaolinite, % | 55-60 | 35-40 | 45-50 |
| Chlorite, % | - | 15-20 | - |
| Mixed layer, % | 20-25 | 15-20 | 5-10 |
| Illite in mixed layer, % | 10-12.5 | 7.5-10 | 2.5-5 |
| Smectite in mixed layer, % | 10-12.5 | 7.5-10 | 2.5-5 |

**Table 2. Fluid formulations**

| WBM #1 | | WBM #2 | | WBM #3 | |
|---|---|---|---|---|---|
| Bentonite , lb/bbl | 5 | Bentonite , lb/bbl | 5 | Bentonite , lb/bbl | 5 |
| Amine acid complex, lb/bbl | 2 | Polyacrylamide, lb/bbl | 2 | Glycol, lb/bbl | 5 |
| Polyacrylamide, lb/bbl | 2 | Aluminum complex, lb/bbl | 3 | Polyacrylamide, lb/bbl | 2 |
| Xanthan Gum, lb/bbl | 1 | Sulfonated asphalt, lb/bbl | 2 | Xanthan Gum, lb/bbl | 1 |
| Sulfonated asphalt, lb/bbl | 2 | Xanthan Gum, lb/bbl | 1.2 | Sulfonated asphalt, lb/bbl | 2 |
| CaCO3, lb/bbl | 30 | Amine acid complex, lb/bbl | 3 | CaCO3, lb/bbl | 30 |
| Lignite/polymer, lb/bbl | 1 | ROP enhancer, lb/bbl | 2 | Lignite/polymer, lb/bbl | 1 |
| **HPWBM, 0.4 % NaCl** | | **HPWBM, 20% NaCl** | | **80/20 NAF** | |
| Bentonite , lb/bbl | 3.0 | Bentonite , lb/bbl | 3.0 | Base oil, bbl | 0.61 |
| NaOH, lb/bbl | 0.75 | NaOH, lb/bbl | 0.75 | Organophilic clay, lb/bbl | 9.0 |
| NaCl, lb/bbl | 68.0 | NaCl, lb/bbl | 68.0 | Emulsifier, lb/bbl | 6.0 |
| Polyacrylamide, lb/bbl | 0.5 | Polyacrylamide, lb/bbl | 0.5 | Wetting agent , lb/bbl | 3.0 |
| Xanthan Gum, lb/bbl | 0.75 | Xanthan Gum, lb/bbl | 0.75 | Lime, lb/bbl | 3.0 |
| CMC, lb/bbl | 0.5 | CMC, lb/bbl | 0.5 | $CaCl_2$, lb/bbl | 120 |
| Modified starch, lb/bbl | 1.0 | Modified starch, lb/bbl | 1.0 | Water, bbl | 0.16 |
| Aluminum complex, lb/bbl | 5.0 | Aluminum complex, lb/bbl | 5.0 | Copolymer, lb/bbl | 3.0 |
| Sealing Polymer, % vol | 3.0 | Sealing Polymer, % vol | 3.0 | CaCO3, lb/bbl | 30.0 |
| Amine acid complex, lb/bbl | 7.0 | Amine acid complex, lb/bbl | 7.0 | | |
| ROP enhancer, % vol | 2.0 | ROP enhancer, % vol | 2.0 | | |

**Table 3 Fluid properties measured after hot rolling at 180°F**

| Properties | WBM #1 | WBM #2 | WBM #3 |
|---|---|---|---|
| PV, cP | 20 | 17 | 22 |
| YP, lb/ 100 $ft^2$ | 14 | 20 | 13 |
| 10-sec Gel, lb/100 $ft^2$ | 8 | 4 | 8 |
| 10-min Gel, lb/100 $ft^2$ | 9 | 4 | 10 |
| API Fluid Loss, ml | 7.2 | 7.2 | 5 |
| | **HPWBM, 0.4 % NaCl** | **HPWBM, 20% NaCl** | **80/20 NAF** |
| PV, cP | 22 | 22 | 39 |
| YP, lb/ 100 $ft^2$ | 11 | 29 | 11 |
| 10-sec Gel, lb/100 $ft^2$ | 4 | 7 | 4 |
| 10-min Gel, lb/100 $ft^2$ | 5 | 12 | 5 |
| API Fluid Loss, ml | 2.6 | 2.4 | - |

**Table 4. Static wafer tests**

| | **WBM #1** | **WBM #2** | **WBM #3** |
|---|---|---|---|
| % Hardness change | 17.02 | 13.83 | 11.7 |
| % Hydration | 9.02 | 6.87 | 7.66 |
| % Swelling | 16.78 | 19.76 | 13.33 |
| **Performance Index** | **42.83** | **40.47** | **32.69** |
| |  |  |  |
| | **HPWBM, 0.4% NaCl** | **HPWBM, 20% NaCl** | **80/20 NAF** |
| % Hardness change | 5.32 | 0.00 | 0.00 |
| % Hydration | 5.94 | 4.22 | 1.15 |
| % Swelling | 15.92 | 1.65 | 2.77 |
| **Performance Index** | **27.18** | **5.87** | **3.92** |
| |  |  |  |

**Table 5. Accretion tests**

| **Composition** | **WBM 1** | **WBM 2** | **0.4% HPWBM** | **20% HPWBM** | **NAF** |
|---|---|---|---|---|---|
| Initial wt | 111.58 | 113.25 | 112.99 | 109.27 | 112.22 |
| Dry wt | 132.35 | 140.65 | 139.69 | 110.87 | 112.35 |
| Solids wt | 20.77 | 27.40 | 26.7 | 1.6 | 0.13 |
| **% Accretion** | **18.6** | **24.2** | **23.6** | **1.46** | **0.12** |

**Table 6**
**Fluid Properties – Case History #1**

| WELL #1 12 ¼" Interval | | | | |
|---|---|---|---|---|
| **Properties Desired** | **Planned** | **Minimum** | **Maximum** | **Average** |
| Fluid Density, lbs/gal | 9.8.-10.3 | 9.7 | 10.3 | 10.2 |
| Plastic Viscosity, cP | 15 -25 | 14 | 22 | 18 |
| Yield Point, lbs/100 ft² | 14 - 25 | 22 | 37 | 27 |
| Gel Strength, 10 seconds – 10 minute, lbs/100 ft² | 5/10 - 10/18 | 7 /10 | 19 /38 | 9/15 |
| 6 RPM Readings | 7 - 11 | 8 | 20 | 10 |
| 3 RPM Readings | 6 - 10 | 5 | 18 | 8 |
| API FILTRATE, ml | <4.0 | 1.68 | 4.0 | 3.1 |
| HTHP FILTRATE, cc @ 150ºF | <10.0 | 7.8 | 12.0 | 9.0 |
| MBT, lbs/bbl Equivalent | 5 – 15 max | 2.5 | 20.0 | 9.6 |

**Table 7**
**Fluid Properties – Case History #2**

| WELL #1 (ST) 12 ¼" Interval | | | | |
|---|---|---|---|---|
| **Properties Desired** | **Planned** | **Minimum** | **Maximum** | **Average** |
| Fluid Density, lbs/gal | 9.8.-10.3 | 10.3 | 10.5 | 10.4 |
| Plastic Viscosity, cP | 15 -25 | 16 | 27 | 21 |
| Yield Point, lbs/100 ft² | 14 - 25 | 18 | 26 | 23 |
| Gel Strength, 10 seconds– 10 minute, lbs/100 ft² | 5/10 - 10/18 | 5 /15 | 12 /29 | 8 /21 |
| 6 RPM Readings | 7 - 11 | 8 | 12 | 10 |
| 3 RPM Readings | 6 - 10 | 6 | 10 | 8 |
| API FILTRATE, ml | <4.0 | 3.20 | 4.4 | 3.7 |
| HTHP FILTRATE, cc @ 150ºF | <10.0 | 8.0 | 10.0 | 9.2 |
| MBT, lbs/bbl Equivalent | 5 – 15 max | 12.5 | 20.0 | 17.2 |

**Table 8**
**Dilution Rates– Case History #1 & #2**

| Well | Total Additions | Distance Drilled | Hole Volume, bbl | Dilution Volume | Dilution, bbl/foot | Consumption, bbl/foot |
|---|---|---|---|---|---|---|
| WELL #1 | 3293.3 | 2703 | 394 | 1157 | **0.44** | **1.22** |
| WELL #1 ST | 2301 | 3122 | 455 | 1863 | **0.60** | **0.74** |

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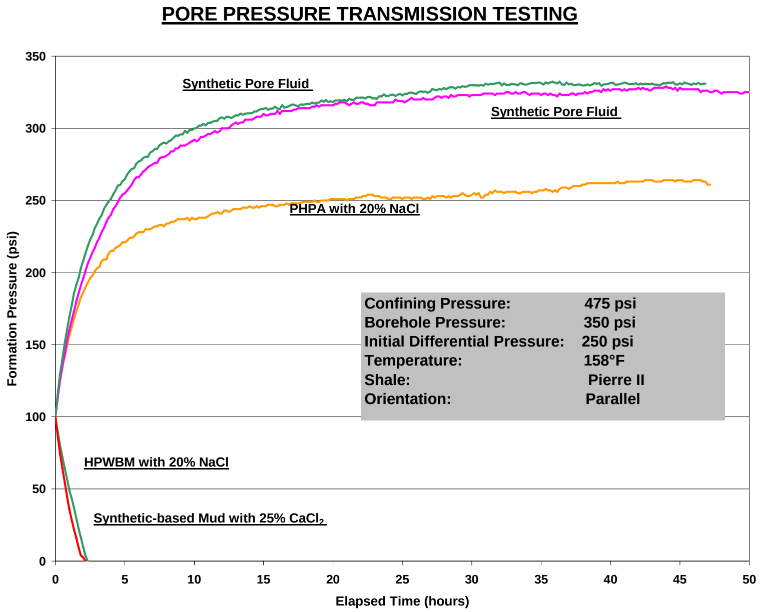


**Figure 1 – PPT test results comparing HPWBM to conventional WBM & SBM**


**Figure 2 –PDC bit from offset wells with conventional WBM**

**Figure 3 –PDC bit WELL #1 with HPWBM on WELL #1**

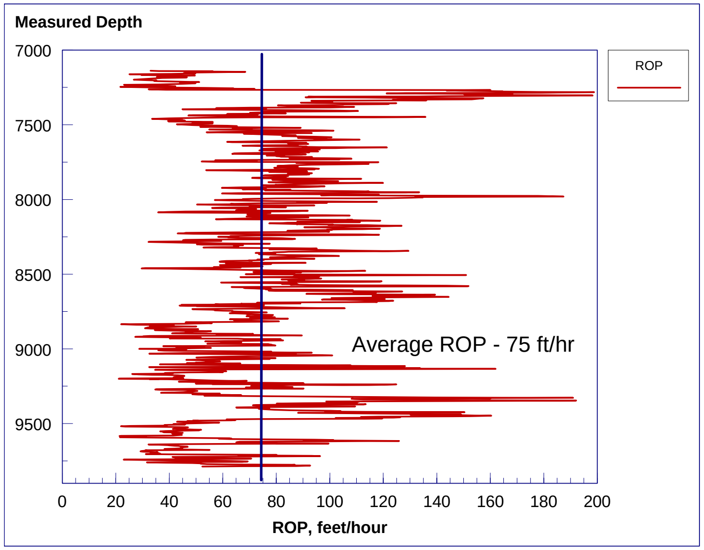


**Figure 4 – Rates-of-Penetration – WELL #1**

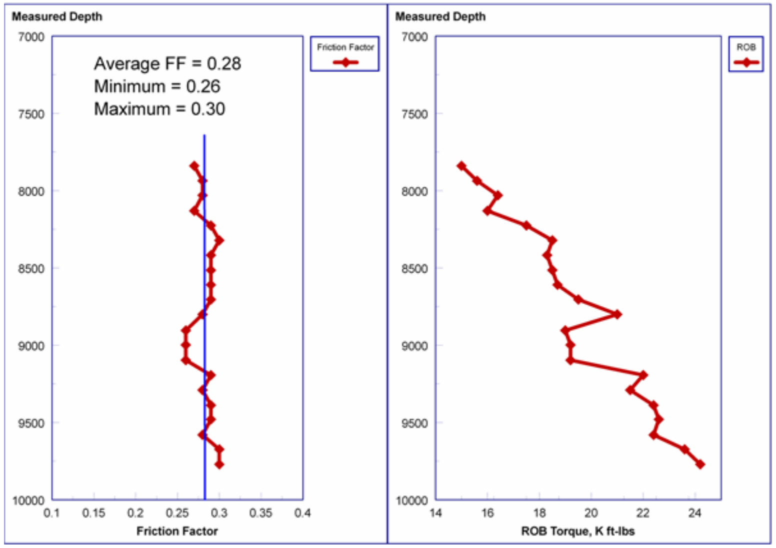


**Figure 5 – Torque and Drag Analysis – WELL #1 ST**

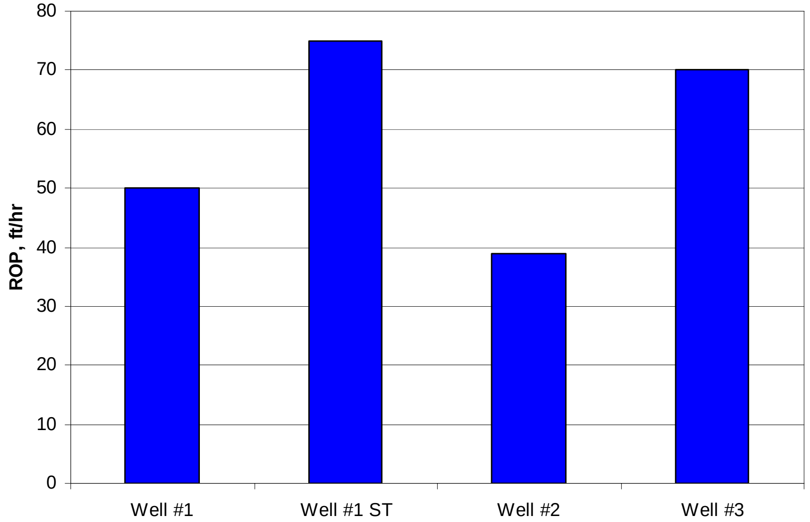


**Figure 7 – Case Histories – Average ROP Comparison**

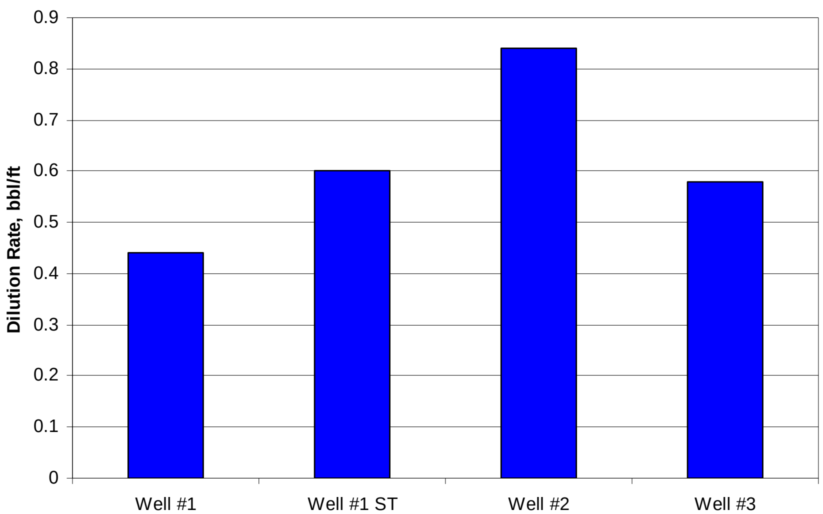


**Figure 6 – Case Histories – Dilution Rate Comparison**

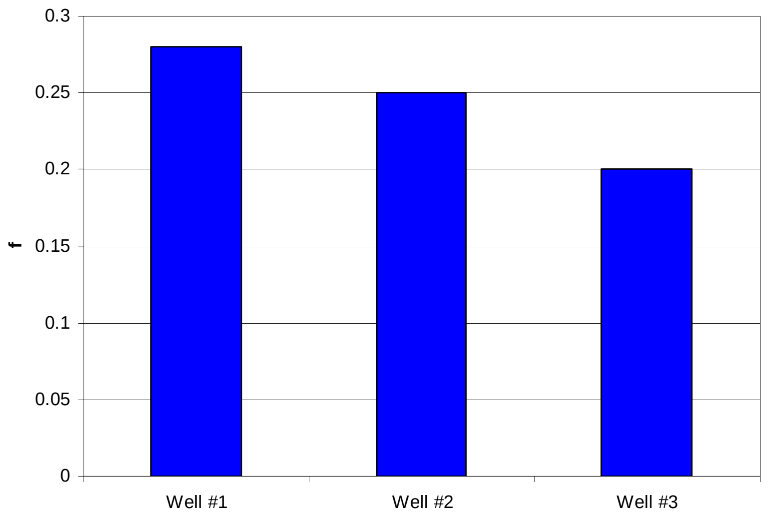


**Figure 8 – Case Histories – Friction Factor Comparison**